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Evidence from Magellan for unexpectedly deep complex craters on Venus

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ABSTRACT

The inverse gravity (1/g) scaling trend for complex crater depths and the shallow depths reported from terrestrial impact structures led to the general expectation that depths of Venusian craters would be Earth-like and considerably shallower than those of the smaller planets like Mars. Pioneer Venus and Venera 15/16 radar observations seemed to indicate very shallow craters as expected; however, the present analysis shows that any crater depth information reported from these missions should be considered only as minimum bounds. I present new estimates of complex crater depths on Venus derived from cross-track distortions in Magellan radar images that reveal that the freshest craters approach those on Mars in terms of their depth/diameter characteristics. Consequently, strict 1/g scaling does not seem to hold for Venus, indicating that other planetary properties, such as the presence of an atmosphere, may have an overwhelming effect on crater depth. Craters with dark floors are distinctly shallower than fresh Venusian craters, indicating their originally bright crater floors probably have been covered by relatively smooth volcanic deposits. Topographic profiles across four complex craters reveal that these structures have rim heights accounting for as much as 50% of the total crater depth. Because there are no complex craters on Earth which have retained their rim crests, reported depths of terrestrial structures may be underestimated by a comparable amount due to rim removal alone. Venusian complex craters may be more useful for reconstructing the original appearance of eroded craters on Earth than either the lunar craters or the simple 1/g scaling previously used.

INTRODUCTION

The morphology of impact craters and basins yields important information on the processes which shape a planet's surface. Fresh craters provide insight into the hypervelocity impact process itself, whereas degraded craters record the nature and extent of subsequent geologic activity. Crater depth (d), measured from the rim crest to the crater floor, is a fundamental morphometric parameter that can be determined in a variety of ways applicable to planetary exploration, including stereo image analysis, shadow measurements, and photoclinometry, as well as laser or radar altimetry. Compilations of crater depth versus crater rim crest diameter (D) have been analyzed for the Moon (e.g., Pike, 1974), Mars (e.g., Pike, 1980), and Mercury (e.g., Pike, 1988). Typical least-squares (power law) fits to measurements of "fresh" craters on these terrestrial planets are summarized in Figure 1. Because complex crater depths tend to decrease systematically with increasing planetary mass, it is widely suspected that surface gravity is the predominant control.

At present, however, the understanding of what controls complex crater depth is plagued by the limitations of the planetary data sets. There are only three well studied planetary bodies with heavily cratered surfaces, the Moon, Mars, and Mercury and they are only different in their surface gravity by a factor of ~2. In addition, Mercury and Mars, although virtually identical in terms of mass, are substantially different otherwise: Mars has a considerable atmosphere and related

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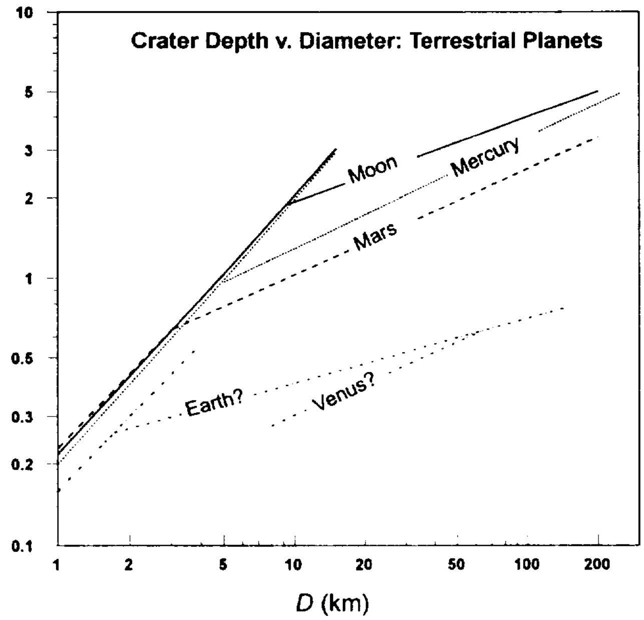

Figure 1. Depth/diameter (d/D) trends for impact craters on the terrestrial planets. The break in slope on each of the trends marks the transition from simple to complex craters. Systematic offsets in d/D trends across these planets have been used as evidence for inverse gravity scaling of crater depths. Least squares regression data for the Moon, Mars, and the Earth are from Pike (1980), for Mercury from Pike (1988), and for Venus from Ivanov (1992). Question marks indicate that there are significant uncertainties in depth estimates of craters on Venus and Earth as discussed in the text.

geological activity; Mercury, like the moon, does not. Consequently atmosphere and various target properties (e.g., strength, volatile content, layering, and other anisotropies) could modulate the process of crater collapse in a way that would not be apparent in comparing crater statistics across only these three planets. In an effort to extend crater comparisons to larger planetary bodies, attempts have been made to compile depth information for complex craters on Earth (Grieve and Robertson, 1979; Pike, 1980; Grieve et al., 1981). Inclusion of terrestrial data in these planetary comparisons extends the range of surface gravity to a factor of six times that of the Moon, and as the so-called inverse gravity or $1/g$ scaling would predict (e.g., Grieve et al., 1981), the terrestrial crater depths (Fig. 1) seem to be considerably shallower than those of the smaller silicate planets.

The last remaining terrestrial planet to yield crater depth information is Venus. Pike (1980) recognized that because Venus is similar to Earth in mass it provided a critical test for the $1/g$ scaling of crater depth across planets. The Pioneer Venus (PV) radar altimeter contributed the first topographic data across suspected impact structures on Venus (Kerr, 1980; Pike, 1980). The limited information available for these features seemed to suggest that crater depths were even shallower than those on Earth and considerably shallower than impact craters on the smaller terrestrial planets. In the mid-1980s the Venera 15/16 radar altimeter collected profiles over 20 impact structures ranging in diameter from 32 to 144 km (Ivanov et al., 1986; Basilevsky et al., 1987). These data also indicated that Venusian craters were considerably shallower than those on Mars or the Moon, although somewhat deeper than PV measurements suggested. Shortly thereafter, Ivanov (1989) estimated depths of 82 impact craters by examining the cross-track distortions of crater symmetry in Venera 15/16 radar images. His results indicated that Venusian craters were indeed shallow (Fig. 1), with depths that were indistinguishable from those of the best-preserved complex craters on Earth. Thus Venus, like Earth, appears to provide convincing evidence for the paradigm that crater depths across the silicate planets follow a simple $1/g$ scaling rule.

In this paper, however, I present new evidence derived from Magellan radar data that indicates Venusian craters are considerably deeper than previously estimated or predicted by $1/g$ scaling. I attempt to reconcile these findings with the previous studies which point to shallow crater depths. Finally, I discuss the implications of these data for understanding the degradation of craters on Venus and for reconstructing the surface appearance of terrestrial impact structures.

CRATER MORPHOMETRY FROM RADAR OBSERVATIONS OF VENUS

Radar altimetry and terrain smoothing

Pioneer Venus and Venera radar altimeter observations have indicated that craters and basins on Venus are like those on Earth and follow the $1/g$ depth scaling rule. These estimates, however, only provide lower limits to crater depths because Venera 15/16, like PV, measured elevations over a 50-km-diameter footprint (Barsukov et al., 1986; Basilevsky et al., 1987) yielding a smoothed representation of crater relief (Ivanov et al., 1986). The resolution of Magellan's radar altimeter is significantly improved over that of these previous missions. Nonetheless, the altimeter's surface footprint varies from 10×12 km at periapsis to 20 km $\times$ 30 km for the polar regions of the mapping phase (Pettingill et al., 1991) and is too broad for the purposes of constraining crater depths. Considering that altimeter pulses are not typically centered on crater floor units or rim crests, and that returns from the blocky rim terraces and ejecta blankets of craters are stronger than from the smoother floor deposits or the narrow rim crests, it is unlikely that depths have been accurately measured for any craters, particularly those below about 70 km in diameter.

Crater depths from radar image distortions

To circumvent the problem of terrain smoothing inherent in altimeter data, crater depths can be calculated from the cross-track distortions in crater wall widths, measured from rim crest to the crater floor, in radar images (Ivanov, 1989, Pettingill et al., 1991). This effect is illustrated in the Magellan image of the 19 km crater Ma Shouzhen (Fig. 2), which shows a marked disparity between the lengths of the eastern and western crater walls. These image distortions result from topography-induced slant-range variations because the radar surface model does not contain topographic information of this resolution (Ivanov 1989, 1990, 1992, Pettingill et al., 1991). Local surfaces that slope away from the radar are extended and those that slope toward the radar are compressed by an amount that depends on radar incidence angle θ and the change in surface elevation h. Consequently, h can be determined by first measuring the apparent horizontal distances r_1 and r_2 between the same two surface elements in each of two images taken at different θ, and then applying the following approximation to the stereo equation:

$$h = \frac{r_2 - r_1}{\cot\theta_2 - \cot\theta_1} \tag{1}$$

Crater depths can be estimated in single radar images by assuming bilateral symmetry in the cross-track direction (i.e., letting $\theta_1 = -\theta_2$), and measuring the apparent rim crest-to-floor distances on either side of the crater (r_1 and r_2). In this case

$$d = h = \frac{r_2 - r_1}{2}\tan\theta \tag{1a}$$

Ivanov (1989) derived depth estimates by this technique using Venera 15/16 image data and Leberl et a!. (1991), Sharpton and Edmunds (1991), and Schaber et al. (1992) have determined depths for several complex craters using this technique on Magellan imagery.

Figure 3 shows the depths of 94 complex craters ranging from D = 18 km to D = 175 km estimated from distortions in Magellan Cycle 1 radar images. The large dispersion in this data set (correlation coefficient R^2 = 0.2) probably reflects several effects including: (i) errors associated with locating the rim crest and the outer boundary of the floor, (ii) errors associated with asymmetries in the actual crater topography, (iii) inclusion of relatively modified craters, as well as fresh craters, and (iv) true variations in crater morphometry. These data are consistent with the examples presented by Leberl et al. (1991) and Schaber et al. (1992). It is clear that the depths of Venu-

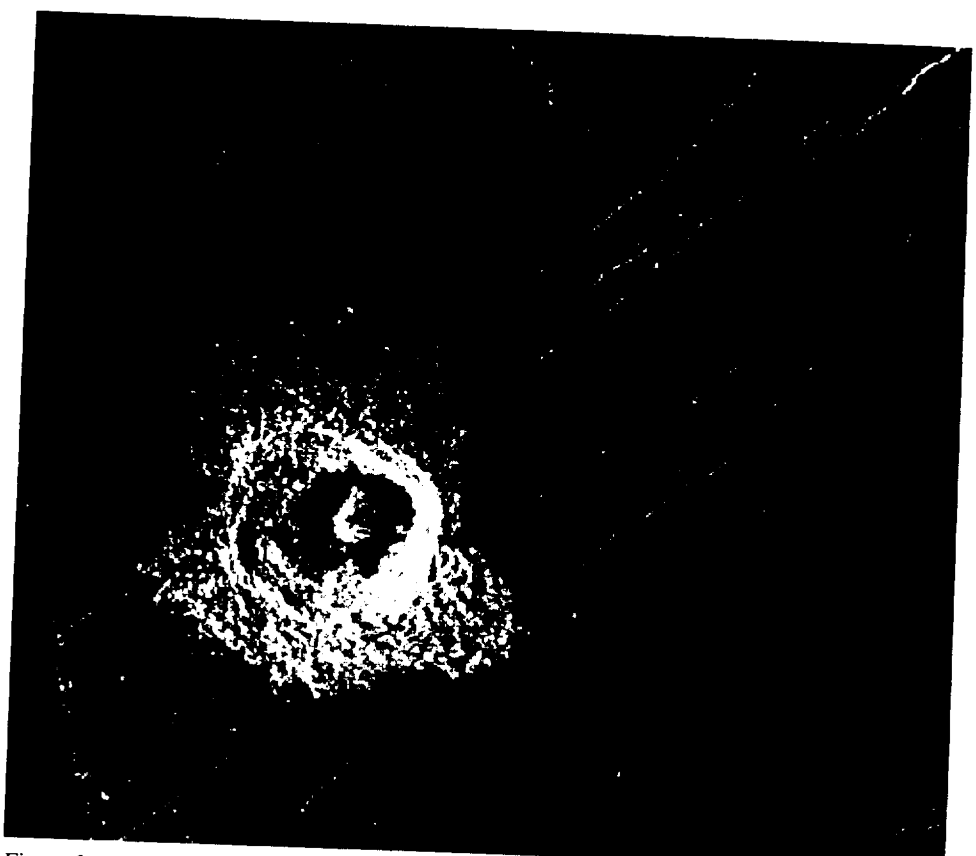

Figure 2. Ma Shouzhen Crater (19 km D). Image is a portion of Magellan Cycle 1 C1-MIDR. The Magellan radar illuminates from the West in this cycle; $\theta \simeq 30°$. Near range crater wall (terrace zone) appears elongated and far range crater wall appears shortened because of the slant range component of height differential.

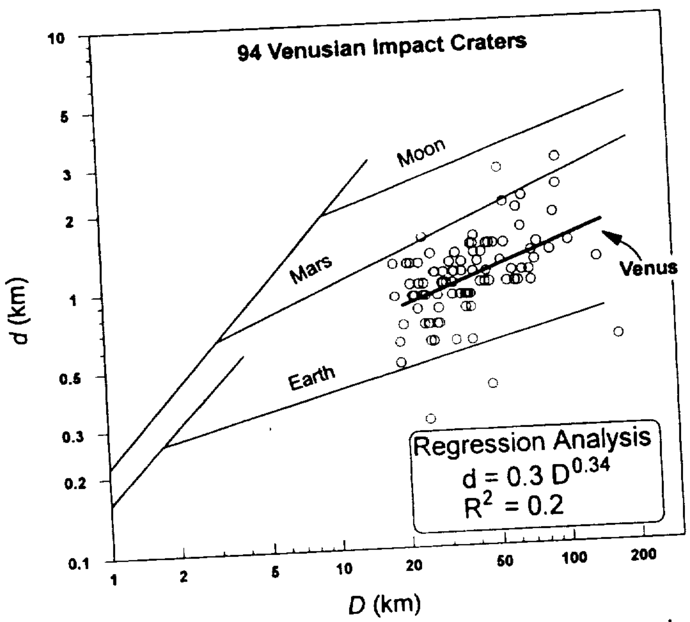

Figure 3. Depth/diameter (d/D) relationship for Venusian craters determined in this study. Narrow solid lines indicate simplified trends of planets shown in Figure 1. Mercury is excluded for clarity. Open circles are individual crater measurements using the image distortion technique described in the text. Bold solid line indicates regression line or Venusian craters.

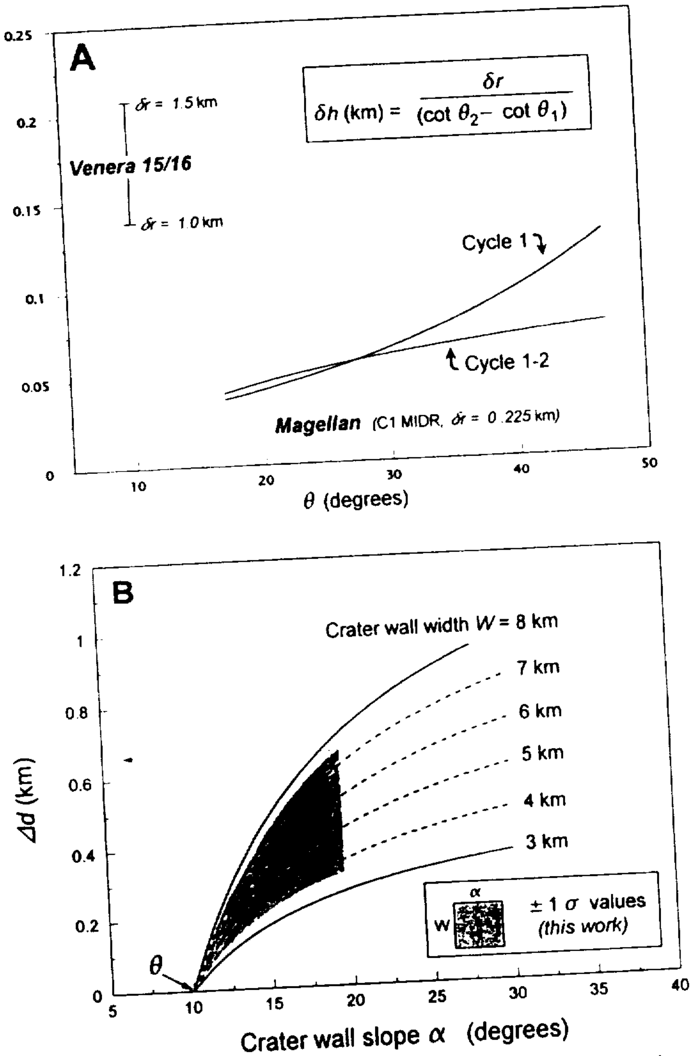

Figure 4. A, Vertical resolution (δh) of the image distortion technique for Magellan and Venera 15/16. Image resolution is δr. B, Effects of foldover on depth estimates. The variable Δd is the amount by which the actual crater depths would be underestimated if the wall slope α exceeds the incidence angle θ. Venera 15/16 incidence angle was 10°.

sian craters as calculated from Magellan image distortions fall considerably above the predicted trend based on gravity-scaling trends across the terrestrial planets, depths reported for terrestrial craters, or pre-Magellan analyses.

Resolution and range constraints. As mentioned above, terrain smoothing imparts a systematic error to crater depths measured by radar altimeters and readily explains the discrepancy between the altimeter based depths and those presented here. Of more concern is the analysis of Ivanov (1989, 1992) that used distortions in Venera 15/16 radar images and concluded that Venusian crater depths were considerably shallower than those presented in Figure 3. Ivanov (1990) noted that the higher incidence angle of the Magellan mission over that of Venera orbiters (~10°) would reduce the utility of using the radar distortions to derive depth measurements, because the differences in apparent rim zone widths (r_1 and r_2) would be reduced. The much improved spatial resolution of Magellan, however, more than compensates for the more favorable incidence angle of Venera for these purposes.

Assuming for the moment that the incidence angle (θ) is ideally constrained, the vertical resolution (δh) of topographic measurements produced from image distortions is proportional to the image resolution (δr) and inversely proportional to θ, in the manner shown in Equation 1. This relationship is shown in Figure 4a. Magellan Cycle 1 images were taken at incidence angles that varied latitudinally from ~17° to 43°; Cycle 2 images maintained a constant 26° incidence angle. For the single-look approach to measuring crater depths the actual error in height calculations depends on δh, plus the error in identifying the rim and floor of a crater, the error of the assumed local incidence angle, the error of measuring the length of the slope, and the crater's lack of symmetry. Excluding asymmetries in crater topography, it is likely that these contributions result in uncertainties that are ~3δh, or approximately ±220 m at the average Magellan Cycle 1 incidence angle (see Leberl et al., 1991). For the Venera 15/16 data the uncertainty could easily exceed ±600 m.

Real departures from the crater symmetry assumed in Equation 1a will result in significant errors to some individual depth measurements. These errors will be randomly distributed about the mean, however, with no systematic preference either to over- or underestimation. Although they have an adverse effect on the apparent dispersion of the data set (reflected in R^2 in Fig. 3), determination of the least squares regression trend should be unaffected by these errors. Because there are only a few craters at large diameters, however, the regression trend is well constrained only for crater diameters below approximately 90 km.

Effects of radar foldover. An effect related to the low incidence angles of Venera 15/16 that Ivanov (1989) apparently did not consider is image foldover; and this probably accounts for most, if not all of the discrepancy between his measurements and those presented here. Equation 1 only holds in the case where the radar incidence angle θ is greater than the (radar-facing) surface slope α. If $\alpha > \theta$, then the surface feature is "folded over" in the image. This occurs on slopes facing the radar because the top is at a shorter slant range distance from the radar than the bottom and so in the image the relative positions of the top and bottom in the cross-track direction are transposed. In such cases, Equation 1 must be modified to

$$d = \frac{r_2 - r_1}{\cot\theta_2 - \cot\theta_1}\tan\theta \qquad (2)$$

or for the single image approach

$$d = \frac{r_2 - r_1}{2}\tan\theta \qquad (2a)$$

Using Equation 1 in cases of foldover would result in an underestimate of the actual depth by an amount

$$\Delta d = r_1 \cot\theta \qquad (3)$$

Foldover can be difficult to ascertain, particularly given the kilometer-scale resolution of Venera 15/16. To evaluate the possibility of rim foldover, I calculated the average slopes across the inner walls (i.e., terrace zones) of the craters presented in Figure 3. The slopes range from 4° to 32° with a mean slope value of 13° ± 7° (1σ). Consequently, it is likely that inner wall slopes of virtually all craters on Venus exceed the 10° Venera 15/16 incidence angle and therefore are folded over in the Venera images to some degree. Figure 4b illustrates the deficit in calculated depth Δd resulting from unrecognized foldover as a function of wall slope α and wall width W. For typical Venusian craters this deficit could be as great at 650 m and may account for the discrepancy between the shallow depths reported by Ivanov (1989) and those presented here.

CRATER DEGRADATION ON VENUS: ORIGIN OF DARK FLOOR DEPOSITS

The freshest 5–10% of craters on Venus have retained regionally extensive parabolic- or circular-shaped deposits of radar-dark distal ejecta (Campbell et al., 1992). These craters also typically have bright blocky floors and dark haloes surrounding their ejecta blankets. Of the 66 such craters identified by Campbell et al. (1992), depths have been determined for 21. Figure 5a shows that this subset of Venusian craters ($20 \le D \le 100$) has depths that are somewhat greater than the total population and are virtually indistinguishable from the martian fresh crater trend. Strict inverse gravity scaling predicts that crater depths on Venus would be approximately one-sixth those on the Moon and one-half those on Mars. The fact that fresh craters on Venus are approximately twice this deep indicates that there are limitations to the 1/g assumption and that other planetary controls must be invoked on Venus.

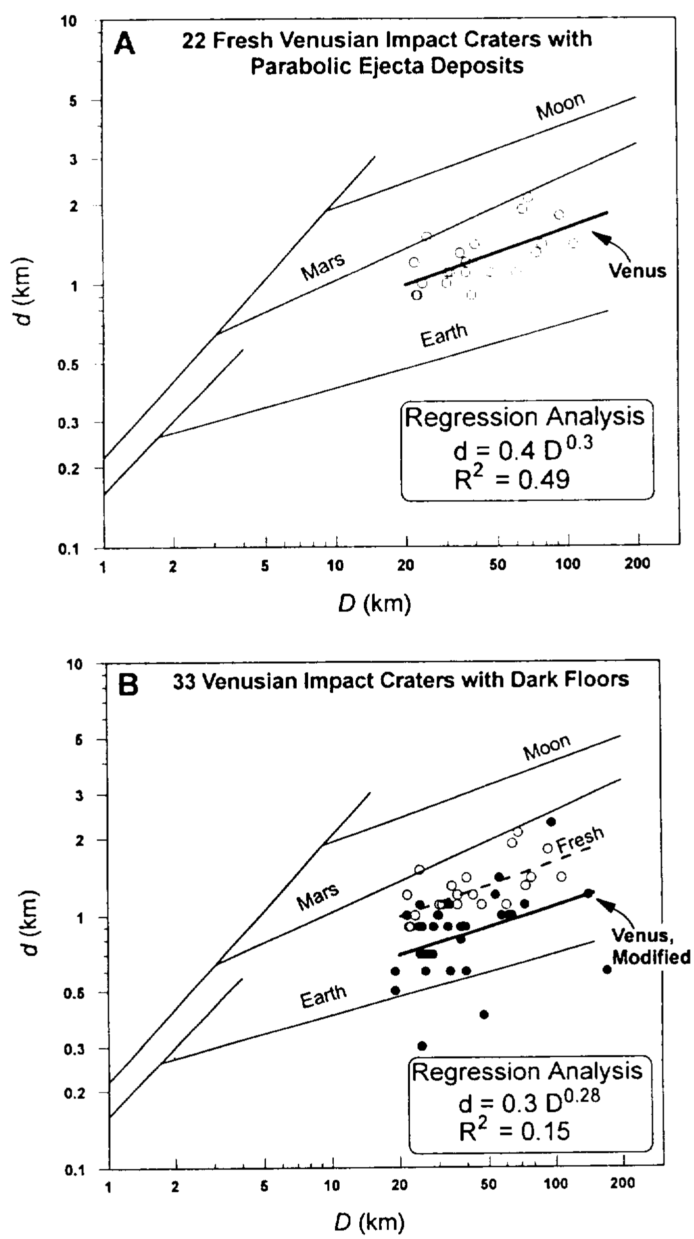

Figure 5. A, Depth/diameter (d/D) relationship for fresh Venusian craters exhibiting radar-dark deposits of distal ejecta. B, Depth/diametir (d/D) relationship for Venusian dark floor craters. Data for dark floor craters are shown as filled circles; open circles indicate data for fresh craters for comparison.

Over 50% of the remaining craters on Venus have low-backscatter floors. In most cases these smooth, radar-dark floor units appear similar to the surrounding plains. Possible explanations for the dark floors include impact melt, darkening due to atmospheric chemistry, aeolian infilling, or volcanism. Campbell et al. (1992) observed that few, if any, craters exhibiting parabolic distal ejecta deposits also show dark floor deposits. Because the retention age calculated from the size-frequency distribution of these craters suggests that distal parabolic deposits persist over time scales of 10^7 to 10^8 yr, it does not appear that the dark floors are produced at the time of or shortly after crater formation. It seems unlikely, therefore, that impact melting or impact-induced volcanism are plausible explanations for the dark floors.

There is considerable variation in terms both of the average backscatter and the distribution of dark floor deposits within Venusian craters. Figure 5b summarizes the depth characteristics of 38 dark floor craters chosen because their floors were distinctly, completely, and uniformly radar dark (smooth). These data reveal a significant difference between the depths of fresh craters (open circles and also in Fig. 5a) and craters with dark floor deposits (filled circles). The power law fit to fresh craters, $d = 0.4\ D^{0.4}$, is steeper and lies above the fit to dark floor craters, $d = 0.3\ D^{0.28}$. A z-analysis of log d/log D demonstrates that these populations are distinct at the 99% confidence level. The significantly shallower depths of dark floor craters suggests that the dark floor deposits are the result of volcanic infilling and probably not weathering effects, which should produce no discernible difference in fresh craters and those with dark floors. A volcanic origin for at least some dark floor deposits is supported by Aglaonice crater (Fig. 6) which exhibits a very dark floor and an ejecta blanket that appears to be embayed by lavas which originate from an east-west trending system of fractures just north of the crater. Dark floor deposits and related peripheral volcanism probably are not impact triggered, as mentioned above. Thus dark floor craters may be evidence of modest but continual volcanic activity over the course of the crater retention age of the Venusian surface, approximately one-half billion years (Schaber et al., 1992; Phillips et al., 1992). The extremely high dispersion ($R^2 = 0.15$; Fig. 5b) characteristic of this subset of Venusian craters suggests that the thickness of the dark floor deposits may vary considerably. On average, however, dark floor craters are 250 m to 400 m shallower than the fresh craters shown in Figure 5a. Assuming that dark floored craters were originally as deep as the craters displaying parabolic distal ejecta deposits, and that their present deviations from these fresh depths are solely due to infilling, the thickness t_m of the deposits modifying dark floor craters follows the power law relation $t_m = 0.08D^{0.3}$.

CRATER PROFILES AND ADDITIONAL CRATER MORPHOMETRY

Using Equation 1, I constructed topographic profiles (approximately west to east, through the crater center) across four impact craters (Fig. 7) covered by Magellan Cycle 1–Cycle 2 image pairs. Guilbert and Budevska are fresh bright-floored central peak craters, Corpman and Flagstad are peak ring structures with dark floor deposits. Corpman contains the most areally extensive dark floor deposits. The depth estimates of these craters support the single image estimates presented above.

Because the techniques of using two radar images does not hinge upon symmetrical topography, individual errors are reduced considerably and morphometric information can be extended beyond simple depth constraints. For instance, rim heights (h_r) of these craters constitute ~0.3–0.5 d and there are slight variations ($\leq 0.3\ h_r$) in the eastern and western h_r for the few craters measured. Crater flanks, mantled by bright, blocky ejecta, are narrow, ranging from ~0.2–0.5 D. Assuming that ejecta constitutes ~0.5 h_r (Melosh, 1989), the continuous ejecta blanket around Budevska crater contains ~400 km^3 of ejecta, equivalent to ~300 km^3 of unfragmented target rock.

Central peak heights vary considerably from ~0.1–1.0 d. The lower extent of this range may be due, in part, to subsequent modification of Corpman by extensive dark floor deposits. The central peak of Guibert protrudes virtually to the level of the rim, and Budevska's central peak is only slightly shorter. Similar large central peaks have been noted in craters on other planets, for example, the lunar farside crater, Icarus (Schultz, 1976), the terrestrial Marquez Dome crater (Sharpton and Gibson, 1990), and Aeneas on Dione (Schenk, 1989). Such craters, however, are relatively rare on other planets; having two such examples within a sample of four craters, suggests that these anomalously tall central peaks might be more common on Venus.

CONCLUSIONS

Evidence of crater degradation on Venus

Dark floor craters on Venus are 150–400 m shallower on average than fresh craters exhibiting radar-dark parabolic deposits of distal ejecta. This, coupled with the observation that the freshest craters do not have dark floors, indicates that dark floor deposits are evidence that over half of the impact craters on Venus have been affected by ongoing volcanic activity over the past half billion years. The few Venusian craters for which topographic profiles have been determined all show unusually high rim crests, as measured from the surrounding surface elevation. If further work on Venusian crater topography confirms that such high rims are characteristic, then this trait could partly explain the observation that although Venus seems to have been quite active in its recent past, it has retained a substantial number of impact craters. High rim zones would better survive regional volcanism that would otherwise inundate the crater topography. Furthermore, because the rims of most dark floor craters are not breached, any interior volcanism would be due to isostatic infilling from below the crater floor, possibly employing impact induced fracture networks.

Figure 6. The dark floor crater Aglaonice (63 km *D*) has additional evidence of volcanic modification. Arrows point to sources of possible lavas which have modified the crater flanks and partially flooded the ejecta blanket.

Fresh crater depths and inverse gravity scaling

The depths of fresh impact craters on Venus are not in accordance with predictions based on the simple inverse relationship between surface gravity and crater depths. Factors that could contribute to deep craters on Venus include (i) enhanced target strength on Venus, possibly related to low volatile content, reducing the efficiency of crater collapse, (ii) more efficient or deeper excavation on Venus, possibly reflecting rheological effects of the hot Venusian environment, (iii) more melting and efficient removal of melt from the crater cavity, (iv) enhanced ejection of material out of the crater, possibly as a result of entrainment in an atmosphere set in motion by the passage of the projectile, or conversely (v) enhanced rim pileup possibly due to atmospheric deceleration of ballistic ejecta or (vi) atmospheric retardation of lateral growth of the excavation cavity (e.g., Schultz, 1992). Thorough evaluation of these alternatives is not possible with the current information on crater topography; however, if crater depth is controlled by rim pileup due to atmospheric deceleration (mechanism v), then this may require excavation and ejection to be more efficient on Venus (mechanisms ii–iv): Because there is no appreciable difference between the widths of ejecta blankets on Venus and those on the Moon, for instance, thicker ejecta blankets (i.e., higher rims) around Venusian craters should contain more material than typical of the smaller silicate bodies. Further investigations, aided by precise three-dimensional crater topography from Magellan stereo-image pairs, could contribute significantly to a better understanding of which, if any, of these mechanisms enhance crater depths on Venus.

Implications for understanding terrestrial crater morphology

Crater depths approximately six times shallower than the lunar crater trend have been reported for terrestrial craters

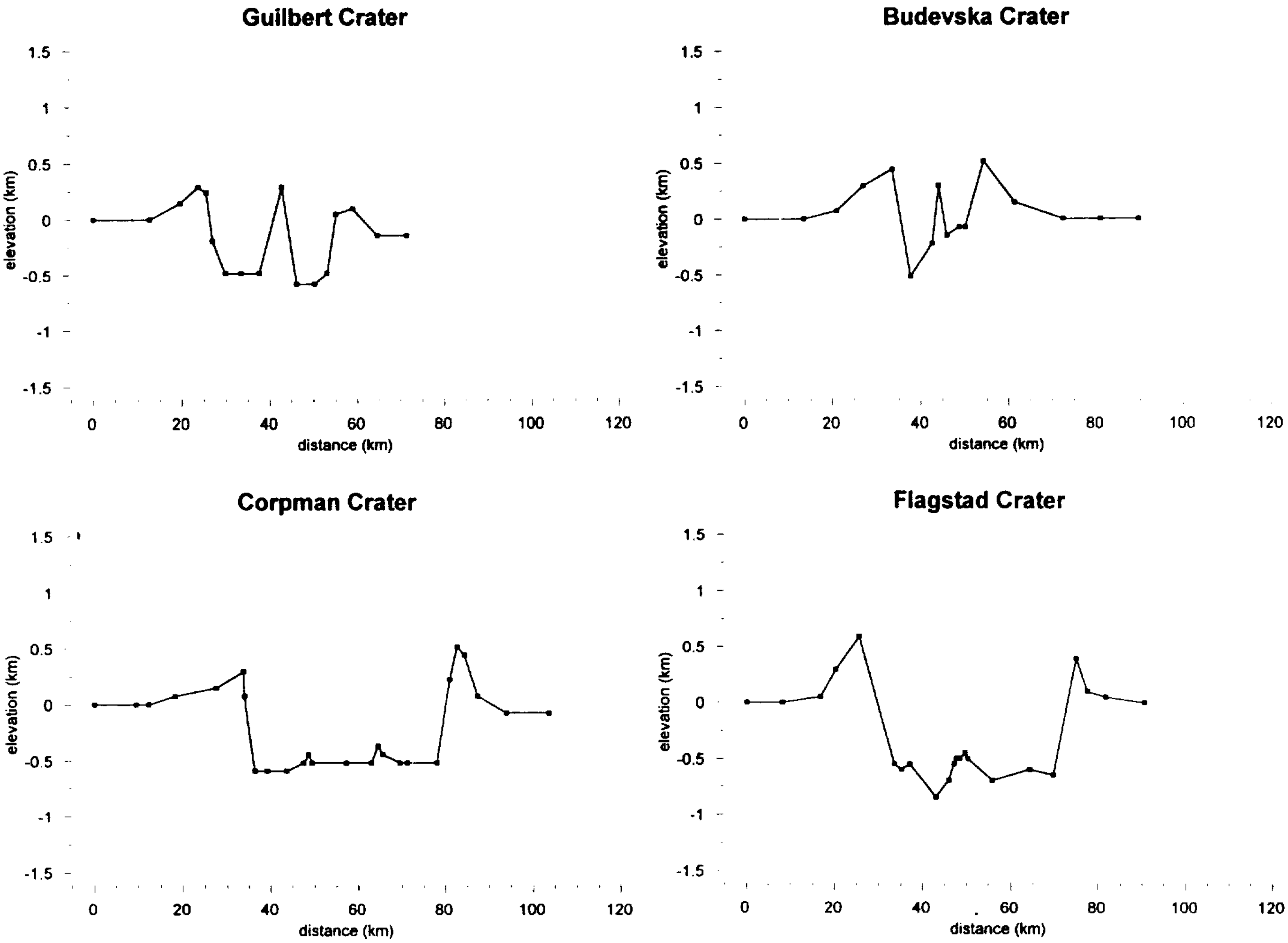

Figure 7. Crater Profiles derived from Magellan Cycle 1–Cycle 2 image distortions. See text for details.

(Grieve and Robertson, 1979; Pike, 1980; Grieve et al., 1981) and used as evidence of 1/g depth scaling. As there are *no* well-preserved terrestrial complex craters with their rim crests intact, however, the depth estimates reported in the literature should be regarded with some caution and considered only as minimum estimates. The Venus data in Figure 7 indicate that rim height is a significant portion of total crater depth, and as all terrestrial complex structures are severely modified by erosion, their depths may be underestimated by up to a factor of two due to rim removal alone. In addition, when the crater rim and ejecta blanket have been removed, it becomes more difficult to determine the rim crest diameter. Given the similarities of Venus and Earth in size and presence of an atmosphere, Venusian craters may provide a better morphological template for reconstructing the original appearances of the heavily eroded terrestrial impact structures than either the lunar craters or simple gravity scaling models which have been used in the past.

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